

# **CEUS Earthquake Hazards Research Review and Planning Workshop**

## *Abstracts*

*University of Memphis*

*February 25-26, 2014*

### **Engineering Ground Motion Issues**

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This presentation discusses epistemic uncertainties that have significant impact on ground-motion prediction equations (GMPEs) for the East. Aleatory uncertainty is also briefly discussed. In eastern North America, GMPEs are driven by simulation-based and/or hybrid models, due to the lack of data to adequately constrain empirical models at the magnitude-distance range of most engineering interest ( $M > 6$ ,  $R < 50$  km). The most important uncertainties controlling predicted amplitudes in the simulation-based models are:

- Source scaling with magnitude (including source-based saturation effects)
- Geometric spreading at distances  $< 100$  km (and its possible frequency dependence)
- Near-distance saturation effects, especially at larger magnitudes
- Effect of site response on GMPEs in the east (probably not the same as the west)

In modeling, there are important trade-offs amongst these parameters, particularly between geometric spreading and stress parameter. This makes it difficult to convincingly constrain simulation-based GMPEs and their uncertainties.

Empirical ground-motion data in the east are improving, but are still insufficient for robust empirical models. However, it is interesting that use of the referenced empirical model, in combination with the new NGA-W2 GMPEs (which are more robust at small magnitudes than the NGA-W1 GMPEs), suggests that eastern motions may be generally similar to western motions, except at large distances ( $> 50$  km) and high frequencies ( $> 5$  Hz).

### **Seismic Hazard and Ground Motion Implications of Induced Seismicity**

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Induced seismicity poses a significant and as-yet-unquantified risk to the integrity of critical structures, such as major dams or nuclear power plants, as new unconventional energy activities (including hydraulic fracture treatments and wastewater disposal) are currently being planned and/or conducted in close proximity (within 10 km). The addition of a new seismicity source, such as a disposal well, fundamentally alters the seismic hazard at nearby sites. The additional hazard from the induced seismicity source may overwhelm the natural hazard, particularly at the low-probability levels of interest to critical structures. The impact is greatest in regions of low-to-moderate seismicity, for which existing facilities were designed with the implicit understanding that expected ground motions are modest. The impact is further exacerbated by the shallow depth of the induced events, which may result in large ground-motion amplitudes being generated from moderate events at very close distances.

This presentation overviews the ground-motion and hazard issues associated with the addition of an induced seismicity source in close proximity to a site, in a low-seismicity region. I show that IF an induced seismicity sequence is initiated, then its contribution to hazard will greatly exceed that from the pre-existing natural hazard. This arises due to the very close proximity of the source to the site, and the fact that the background hazard is low. Therefore, it is crucial to assess the likelihood and rate parameters of the potential induced seismicity sequence; this would allow us to multiply the hazard parameters for the induced-seismicity source by the appropriate conditional likelihood parameters, and obtain a reasonable estimate of the added hazard. Characterizing the hazard contributions of induced seismicity sequences, for operations that have not yet been initiated, is a complex problem that will provide a grand challenge in engineering seismology over the coming decade.

## **Quaternary Earthquake Source Criteria for the National Seismic Hazard Maps**

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In probabilistic seismic hazard analysis we estimate the rate of exceeding a specified level of ground motion. This information is typically presented in a hazard curve, which for a given earthquake source, is the product of the earthquake's annual rate times the probability that the earthquake exceeds each one of a set of potential ground motions. From the hazard curve we extract the ground motions that are exceeded at probability levels of engineering interest, for example a 10% chance or 2% chance in 50 years. Calculating hazard from a particular earthquake source requires having an estimate of the earthquake's: location, magnitude, geometry, mechanism, and return period. Many faults exist within the Earth's crust, but only a small subset of them are known to be active in the present stress field. In our hazard analysis, we only consider active faults with documented rupture in the Holocene or Late Pleistocene.

We make use of three primary types of earthquake sources in the USGS National Seismic Hazard Maps: 1) background earthquake sources, 2) areal earthquake sources, and 3) specific fault sources. The background earthquake source model is used where specific fault candidates have not been identified or studied in adequate detail. It is derived from a declustered earthquake catalog, regional estimation of the maximum magnitude in a truncated exponential earthquake magnitude-rate relationship, estimation of regional b-values, which requires an estimation of the completeness of the range of observed magnitudes, and computation of smoothed a-value grids. Areal sources are used for characteristic or repeating large magnitude earthquakes where large earthquakes are known to have occurred, but again, specific fault candidates have not been identified or studied in adequate detail. Examples for the 2014 USGS National Seismic Hazard Maps include earthquakes near Charleston, South Carolina, earthquakes in the Wabash Valley in Indiana and Illinois, and earthquakes near Mariana, Arkansas. The final source model for the NSMHs is a fault source model where a specific fault is identified and earthquakes are confined to rupture along a fault with given geometry. Examples include the Meers fault in Oklahoma, Cheraw fault in Colorado, and the New Madrid fault system in the upper

Mississippi River Valley. For the two former source models, we assume a variety of source mechanisms and geometries that are consistent with earthquake focal mechanisms and the existing stress field. For the two latter, paleoseismic studies typically provide information on earthquake recurrence. Paleoseismic studies also provide information on fault geometry and source mechanism for fault specific sources.

### **Evidence of the Eastern Tennessee Seismic Zone in Southeastern Kentucky**

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A magnitude 4.2 earthquake in southeastern Kentucky on November 10, 2012 provides evidence that the Eastern Tennessee Seismic Zone (ETSZ) continues farther north than previously recognized. This earthquake was well recorded by regional networks and the Transportable Array component of the EarthScope project, which allowed precise determination of the source parameters and the detection of aftershocks. We find that the main-shock's focal mechanism is consistent with mechanisms determined for ETSZ earthquakes to the south, both in terms of the style of faulting (predominantly strike slip) and in the strike of the steeply-dipping nodal planes. Also, we observe that the focal depth is consistent with the trend of larger (M3.5+) ETSZ earthquakes, which tends to increase from south to north. Additionally, including this earthquake, we note that nearly one-third (four of thirteen) of all magnitude 3.9 and greater earthquakes have occurred in southeastern Kentucky, which provides reason enough to consider southeastern Kentucky to be in the ETSZ.

There is a well-documented spatial correlation between the ETSZ seismicity and the New York-Alabama magnetic lineament (NYAL): the majority (70-90%) of seismicity occurs to the southeast and proximal to the NYAL. In contrast to central ETSZ seismicity, we observe that in northeastern Tennessee and southeastern Kentucky, north of 36.2°N, earthquakes are more diffuse and tend to occur on the northwest side of the NYAL, including all M 3.9 and larger earthquakes. The Kentucky Seismic and Strong-Motion Network installed a new seismic station in southeastern Kentucky following the 2012 earthquake, to improve the monitoring in what seems to be the northern extent of the ETSZ.

### **Paleoseismic Evaluation of ETSZ: Importance of Evaluating Origin and Uncertainty for New Paleoseismic Data for Seismic Source Characterization in CEUS**

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The recently published Central and Eastern United States (CEUS) Seismic Source Characterization (SSC) for Nuclear Facilities (EPRI, DOE, NRC, 2012) provides guidance for the completion of probabilistic seismic hazard assessments (PSHA) at nuclear facilities in the CEUS. In CEUS SSC, 2012, the spatial and temporal distribution of future earthquakes is modeled by two types of seismic sources. The first type is a distributed seismicity source, which is based on observed seismicity. The second type is a repeated large-magnitude earthquake (RLME) source, which is based on the paleo-earthquake record. RLMEs represent separate sources of seismic hazard in addition to the more regional distributed seismicity sources. RLMEs are defined as those unique areas with clear, compelling evidence of repeated large-magnitude ( $M \geq 6.5$ ) earthquakes and estimates of magnitudes and recurrence intervals from the historical or paleo-earthquake record (i.e., New Madrid and Charleston Seismic Zones).

The Eastern Tennessee Seismic Zone (ETSZ) is as an area characterized with high rates of historical seismicity, but is not explicitly included as a distinct seismic source in the CEUS SSC model. The ETSZ area was modeled as part of the larger Paleozoic Extended Crust seismotectonic zone (PEZ) characterized with large  $M_{max}$  values and spatial smoothing of seismicity to retain local high seismicity rates. Since publication of the CEUS SSC report, researchers have continued to investigate possible paleoseismic evidence for large magnitude paleoearthquakes in the ETSZ. Characterization of this evidence, including assessing uncertainty and alternative, non-seismic origins is critical to the proper evaluation of, and site-specific applications of the CEUS SSC.

Our study evaluated numerous potential paleoseismic features located in the ETSZ as described by Hatcher et al. (2012). These types of potential paleoseismic features found near Douglas Reservoir in East Tennessee (including fractures, filled fissures, low angle shear planes, soil mixing) commonly have alternative non-seismic origins unlike the more diagnostic tectonic features such as fault scarps or folds. Our evaluation focused on assessing whether these features may be tectonically related, determining the level of uncertainty in alternate interpretations, and considering how we would apply the information to the possible development of an RLME for the ETSZ region or other modifications to the CEUS SSC model. Detailed Quaternary terrace mapping around Douglas Reservoir was performed to assess relative age relationships among Quaternary deposits that host the potential paleoseismic features identified in the area. Pedologic and paleoseismic analysis of these terrace deposits and the anomalous features described within them were evaluated in wave cut and shallow trench exposures.

Our results show that the features are compelling and may be related to seismic activity such as strong ground shaking, but may not be directly seismogenic. We therefore consider multiple working hypotheses for the nontectonic origin of these features, including mass movement, pedogenic processes, and to a lesser extent, karst-related collapse or subsidence. Further paleoseismic investigations could help resolve uncertainties and test alternative interpretations. Additionally, estimated ages of potential paleoearthquakes in the ETSZ have not been determined such that repeat times between earthquakes can be estimated. The current level of uncertainty regarding the origin and temporal relationships of potential paleoseismic features identified in the ETSZ near Douglas Reservoir is significant. The current understanding of the data from these features is not sufficient to develop estimates of magnitude and recurrence for paleoearthquakes in the ETSZ region.

## **Paleoseismology and seismic source zones south of the New Madrid seismic zone and the East Tennessee seismic zone**

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Holocene sand blows are present to the south of the New Madrid seismic zone in the Mississippi Valley of east-central Arkansas near the southern end of the northeast-striking Reelfoot rift and on the Gulf of Mexico Coastal Plain south of the Reelfoot Rift system. Large sand blows in east-central Arkansas record at least two paleo-earthquakes in mid-early Holocene. These sand blows are near the intersection of the northwest-striking White River fault zone and the east margin of the Reelfoot rift. On the Coastal Plain in southeast Arkansas and northeast Louisiana, modern seismicity is low, but the distribution of sand blows there record at least four strong Holocene paleo-earthquakes from more than one seismic source. Southeast Arkansas sand blows are found close to Pleistocene and Holocene surface ruptures on several faults of the northwest-striking Saline River fault zone, suggesting this fault zone has a significant seismogenic potential (M6 to 7). Seismic reflection profiles show that the Saline River fault zone is a graben system related to an episode of Triassic rifting during initial opening of the Gulf. A prominent flower structure occupies the principal graben, indicating a later phase of compression. The Saline river fault zone follows the Alabama-Oklahoma transform margin of the North American craton on the south.

The northeast-trending East Tennessee seismic zone has one of the highest rates of seismicity in eastern North America although historic damaging earthquakes have been rare. Most of the modern seismicity is in the Proterozoic basement beneath the Appalachian thrust sheets, and the associated faults are poorly understood. In an effort to document the paleo-earthquake record and assess the zone's seismic potential, fieldwork has revealed several sites with Quaternary deformation. These sites include a northeast-striking Pleistocene normal fault in the vicinity of greatest seismicity and, further east along the same trend, a Late Pleistocene northeast-striking thrust fault. Magnitudes of paleo-earthquakes are estimated to be ~M 7 based on the length of epicenter alignments interpreted to be faults and on Quaternary surface fault displacements. Too little data is available at present to estimate a recurrence interval for strong earthquakes in the East Tennessee seismic zone.

### **GMPEs, Q, and NGA East**

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U.S. Geological Survey (USGS) NEHRP grants are supporting research using the Next Generation Attenuation (NGA) East ground motion database. We, and colleagues at CERI, have



been involved with the development of the NGA East database as well as the application of the database in earthquake hazard research. Our research supports both the National and CEUS earthquake hazard reduction goals of the USGS. As part of our research efforts, we have investigated current GMPE model bias and ranking using the NGA East database as a standard of comparison. We have investigated the location and sharpness of the Q transition among the western US, central and eastern US, and Gulf Coast regions west of the Mississippi River using the NGA East database and additional USArray earthquake observations. We are also examining and improving regional Q estimates in various subregions of the CEUS. As a means of exploring its characteristics, we have developed an initial empirical ENA GMPE using the NGA East database. Additionally, we are estimating ground motions from historical intensity observations for  $M > 6$  earthquakes to better constrain ground motion models for larger ENA earthquakes. All these research efforts complement our urban seismic and liquefaction hazard mapping in the CEUS (Memphis, St. Louis, Charleston SC) through updates to the USGS National Seismic Hazard Mapping Project products.

### **Developing Ground Motion Estimates from $M > 6.0$ Earthquake Intensity Observations for Use in ENA Empirical GMPEs**

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Instrumental ground motion observations for eastern North America (ENA) earthquakes are limited to  $M < 6.0$ . Intensity observations for  $M > 6.0$  ENA earthquakes are available. I convert intensities to ground motion estimates for use as constraints in empirical ground motion prediction equation (GMPE) development. My intensity to ground motion conversion uses the relations of Dangkua and Cramer (2011) for ENA. For a given intensity level, the ground motion estimate is assigned to the mean log distance for that intensity and for a given earthquake. This methodology is validated using the 1988 M5.9 Saguenay, QC and 2011 M5.7 Mineral, VA earthquakes, which have both ground motion and intensity observations. Magnitudes of historical events are taken from Cramer and Boyd (2014) for M7 ENA earthquakes. Magnitudes of M6 historical earthquakes are confirmed using the mean intensity Monte Carlo approach of Cramer and Boyd (2014) with the 1925 M6.2 Charlevoix, QC and 1988 M5.9 Saguenay, QC earthquakes as reference events. Mean magnitude estimates for the 1843 Marked Tree, AR and 1870 Charlevoix, QC earthquakes are M5.9–6.0 and M6.0–6.1, respectively. 95% confidence limits on the magnitude estimates are  $\pm 0.3$ –0.4. The 1870 earthquake magnitude estimate is consistent with Ebel (2013). The intensity data for the 1895 Charleston, MO earthquake is too contaminated by site effects (Bakun et al., 2003) to be useful at this time. For use in GMPE development, only the M7 1811–1812 New Madrid and 1886 Charleston, SC earthquakes plus the M6.2 1925 Charlevoix, QC earthquake provide useful additional constraints over a distance range of 50 to 1200 km. The 1929 M7.2 Grand Banks earthquake only provides constraints at large distances of 1200 to 1400 km due to the offshore location of the event. Other historical events are in the magnitude range of existing ground motion observations or the 1925 event, and hence not as useful.

### **Viewing Post-orogenic Landscapes Through the Lens of Tectonic Geomorphology**

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The 2011 M5.8 Virginia Earthquake is the most recent reminder that the eastern margin of the United States does not fit the traditional paradigm of a passive-margin. The historical record provides numerous examples of earthquake activity throughout the eastern U.S. and geologic and geomorphic evidence described in several recent studies suggest vertical motion of the earth surface occurred in the region during the late Cenozoic. It is likely that the causes for historical seismic activity and late Cenozoic deformation are related suggesting that opportunity lies in approaching earthquake hazard research along the eastern seaboard from a new prospective. Tectonic geomorphology provides a convenient framework to document spatial and temporal trends of deformation at the earth's surface. While the basis of tectonic geomorphology lies in tectonic active regions, many of the concepts and theories are transferable to post-orogenic settings. For example, rivers are sensitive to vertical displacements and river morphology and deposits provide a means to characterize differential motions at the earth's surface. Here we summarize the findings and implications of several studies that apply tectonic geomorphology in the southern and central Appalachians and in the epicentral region of the Virginia Earthquake. These studies document features preserved in the fluvial record that are best described by late Cenozoic differential rock uplift and have important implications regarding seismic hazards in the respective study locations. When combine with geophysical investigations, these findings have the potential to elucidate the processes responsible for seismic threats in the eastern U.S. We conclude by discussing potential applications of similar methodologies elsewhere in the region and how such studies can aid earthquake hazard research in the highly populated eastern U.S.

### **Recently acquired LiDAR across the New Madrid Seismic Zone reveal new earthquake-triggered landslides**

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Recently acquired LiDAR spanning the New Madrid Seismic Zone have the potential to provide new insight into the paleoearthquake record in the region. The bare-earth, digital-elevation models derived from these LiDAR data have a spatial resolution of 0.5 m and reveal new details of topography, otherwise obscured by the region's dense forest canopy. This investigation focuses on deep translational and rotational landslides along the bluffs east of the Mississippi River in western Tennessee, which have been previously interpreted to have been triggered by the M7–8 1811–1812 New Madrid earthquake sequence. Our analysis of airborne LiDAR data suggests the possibility of multiple generations of landslides, possibly triggered by older, similar magnitude earthquake sequences circa 1450 and about 900 A.D. We have remapped recent landslides along two sections of the bluffs: a northern section near Reelfoot Lake and a southern section near Meeman-Shelby State Park (20 km north of Memphis, Tennessee). Our mapping confirms much of the previous landslide mapping and reveals new, undetected landslides. Importantly, we observe that the landslide deposits in the Reelfoot region are characterized by rotated blocks with sharp uphill-facing scarps and steep headwall scarps, indicating youthful, relatively recent movement. In comparison, landslide deposits near Meeman-Shelby are muted in appearance, with headwall scarps and rotated blocks that are extensively dissected by gullies, indicating they might be an older generation of landslides. Because of these differences in

morphology, we hypothesize that the landslides near Reelfoot Lake were triggered by the 1811–1812 earthquake sequence and that landslides near Meeman-Shelby resulted from shaking associated with earlier earthquake sequences. To test this hypothesis, we will evaluate differences in bluff height, local geology, vegetation, and proximity to known seismic sources. Furthermore, planned fieldwork will help evaluate whether the observed landslide displacements occurred in single earthquakes or if they might result from episodic movements associated with a sequence of multiple prehistoric earthquake. We anticipate that LiDAR data spanning the New Madrid Seismic Zone will provide new insights into the prehistoric earthquake record in this region.

### **Quaternary geology in the Mississippi River valley**

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The northern Mississippi Alluvial Valley is divided into Western and Eastern Lowlands separated by Crowley's Ridge. This ridge is an uplift block formed by a basal Tertiary marine deposit. Overlying pre-Pleistocene Mississippi River gravel and Pleistocene loess create most of the relief.

The Mississippi River occupied the Western Lowlands prior to 20ka, first as a meandering stream ~80ka and later as a braid stream, leaving a series of loess-covered terraces, ranging from 70-24ka. After the Mississippi River abandoned the Western Lowlands, local streams occupied the braid channels and evolved into the present meandering channels. One of these, the L'Anguille River, cut through Crowley's Ridge to form Marianna gap approximately 17ka.

While the Mississippi River occupied the Western Lowlands, the Ohio River flowed through the Eastern Lowlands, but only a narrow band of these deposits is preserved adjacent to Crowley's Ridge. After ~20ka the Mississippi River abandoned the Western Lowlands to occupy the Eastern Lowlands, removed most of the Ohio River deposits, and initially aggraded thick sand and gravel derived from the glacier to the north. During deglaciation (14-10ka) discharge exceeded the sediment load and the river progressively incised into its older deposits, leaving a series of braid-stream terraces and a broad braid plain at the terminal Pleistocene.

After meltwater flow down the Mississippi River ceased about 10ka, the sediment load changed from dominantly glacial-derived sand and gravel to a mixed load of sand, silt, and clay derived from the drainage basin and channel morphology changed from braided to meandering. This meander belt has been in a stable position north of Marked Tree, AR during the Holocene and occupied only part of the youngest braid plain. Here the river has aggraded, forming extensive sandy point-bar deposits and cutting off meander bends filled with clay. Beyond the meander belt is backswamp where clay aggraded over the braid-stream surface, filling the low-lying area between the meander belt and the youngest terrace. South of Marked Tree, the Mississippi River has avulsed and multiple meander belts are separated by backswamp clay.

The location of tectonically active areas, including the New Madrid Seismic Zone and Mariana gap, within the Mississippi Valley provides an ideal location to identify subtle deformation over a relatively long time interval because river gradients, pathways, and channel styles are all susceptible to minor deformation. Continuing fluvial and eolian deposition through at least 100k provide the possibility of preserving those responses at different locations.



## **Origin of Earthquakes in the EUS**

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In contrast with plate boundary earthquakes, eastern U.S. intraplate earthquakes have never been satisfactorily explained, and their cause has been debated for decades. Various geologic features have been proposed as being capable of distorting and concentrating the otherwise nearly uniform stress field. The recent EPRI evaluation and probabilistic assessment of eastern U.S. earthquake hazards attempted to partly associate these earthquakes with “Iapetan rift-related” features. Previously, the earthquakes have been associated with igneous bodies of contrasting density with their surroundings, or with reactivation of suitably oriented faults. Others have suggested the currently active zones are ephemeral and will be active for a few hundred to a thousand years, then cease activity and other zones will become seismically active.

Demonstrated paleoseismic recurrence of large earthquakes in these zones spanning of thousands of years indicates this hypothesis has limited validity.

The two most active eastern U.S. seismic zones, New Madrid and East Tennessee, have been linked to the Reelfoot rift and the New York-Alabama lineament, respectively, but neither of these hypotheses fits existing geologic and geophysical data. New Madrid seismic zone (NMSZ) seismicity has also been suggested to be related to deep-mantle changes produced by the Farallon Plate. Seismicity, and surface geologic and paleoseismic data in the NMSZ, are best explained today by the dextral strike-slip fault-thrust transfer (stepover) model. Seismicity in the East Tennessee seismic zone (ETSZ) has been demonstrated to have produced earthquakes  $>M = 7$  and recurrence over several thousand years, but an effective model to explain this seismicity has yet to emerge, although a spatial association with the New York–Alabama lineament exists. The ETSZ extends from northern Georgia to just northeast of Knoxville, Tennessee. The highest topography in the Appalachians occurs immediately east of the seismic zone and the shape of one mimics that of the other. Association of this high topography with the ETSZ permits reactivation of part of the NY-AL lineament without having to reactivate all of it.

Eastern U.S. seismicity in the NMSZ, ETSZ, Charleston, Wabash Valley, New England, and central Virginia each appears to be associated with a different set of ancient geologic features or not, suggesting either: (1) a unique source for seismicity in each zone, possibly lower crustal or even lithospheric; (2) little association with ancient geologic features; or (3) insufficient data to explain the seismicity, hence the multiplicity of solutions.

## **Geoscience lessons learned from the 2011 Mineral, Virginia earthquake**

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The 2011 Mineral, Virginia earthquake ( $M_w$  5.8) in the Central Virginia seismic zone (CVSZ) was the largest and most damaging in the central and eastern U.S. since the 1886 Charleston, SC earthquake (Horton et al., 2014). Damage to structures 130 km to the northeast in Washington, DC is consistent with source directivity, soft-soil ground-motion amplification, and anisotropic wave propagation with least attenuation parallel to the northeasterly Appalachian tectonic fabric (Horton and Williams, 2012; Hough, 2012; McNamara et al., 2014).

The earthquake occurred in crystalline rocks within Paleozoic thrust sheets of the Chopawamsic terrane. The reverse-fault mainshock and majority of aftershocks defined the previously unknown, southeast-dipping Quail fault zone, and shallow aftershocks delineated outlying faults (Horton et al., 2012a, 2012b). The earthquake induced minor liquefaction sand boils, but there was no evidence of a surface fault rupture (Horton and Williams, 2012). Geologic mapping in the epicentral area (Spears et al., 2013; Burton et al., 2014) records early Paleozoic accretion of a volcanic arc, plutonism, regional metamorphism, and deformation, with late Paleozoic transpressional faulting and retrograde metamorphism followed by intrusion of Jurassic diabase dikes into extensional fractures. Trenches near the updip projection of the Quail fault zone expose late Paleozoic mylonite zones and faults that offset surficial deposits dated as Quaternary (Burton et al., 2014).

Airborne geophysical surveys reveal additional structural information (Shah et al., 2013). Near the mainshock epicenter, changes in gravity, magnetic, and radiometric anomalies suggest a major bend in geologic structures. Models of gravity anomalies suggest shallow (2-4 km depth) low-density rock within the hanging wall of the mainshock fault plane that extends >20 km from the epicentral area. Outlying clusters of shallow aftershocks locally occur along gravity gradients near crosscutting magnetic anomalies attributed to Jurassic diabase dikes. Also, local reactivation of pre-existing faults is suggested by outlying shallow aftershocks that cluster where linear radiometric potassium anomalies coincide with LiDAR lineaments and mapped shear zones containing muscovite or K-feldspar.

Progress is being made toward identifying and characterizing faults, interpreting other surface features caused by seismic ground motion, and understanding how strain may be locally influenced by pre-existing structures. Further research is needed to understand fault slip rates, evidence for past earthquake magnitudes and recurrence, factors controlling locations of earthquake rupture, and why faults in the CVSZ appear to be more active historically than in adjacent areas.

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## **Earthquakes and geological structures of the St. Lawrence Rift System**

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The St. Lawrence Rift System (SLRS), which includes the Ottawa-Bonnechere and Saguenay grabens, is located well inside the North American plate. Most historic and the some 350 earthquakes recorded yearly occur in three main seismically active zones, namely Charlevoix (CSZ), Western Quebec (WQSZ), and Lower St. Lawrence (LSLSZ)). Outside these areas, most of the Canadian Shield and bordering regions have had a very low level of earthquake activity. In the SLRS, moderate to large earthquakes (Moment magnitude (**M**) 5.5 to **M** 7) are known to have occurred since 1663 causing landslides and damage mostly to unreinforced masonry elements of buildings located on ground capable of amplifying ground motions. Most earthquakes in these seismic zones share common characteristics such as mid- to upper crustal focal depths, no known surface ruptures and proximity to SLRS faults. Variations also exist such as vast seismically-active region (WQSZ and LSLSZ), presence of a large water body (CSZ and LSLSZ), and absence of SLRS faults near concentration of earthquakes (WQSZ). The CSZ is the best studied seismic zone and there, earthquakes occur in the Canadian Shield, mostly in a 30 X 85 km rectangle elongated along the trend of the St. Lawrence River with local variations in focal depth distribution. Faults related to the SLRS and to a meteor impact structure exist and earthquakes occur along the SLRS faults as well as in between these faults. Two local factors can lead to the occurrence of SLRS earthquakes: weak faults or enhanced stress levels. We propose that local conditions, concentrated in a few seismic zones, can alter these factors and lead to the occurrence of earthquakes, especially those with **M** < 4.5. At a continent-wide scale, the correlation between the SLRS and earthquakes is appealing. We suggest, however, that pre-existing faults related to the SLRS do not explain all features of the seismicity. Seismicity is concentrated in more active areas, some with conspicuous normal faults and some with suspected weakening mechanisms such as intense pre-fracturing (e.g. due to a meteorite impact), the passage over a hot spot, or the presence of intrusions and lateral crustal density variations.

## **Lg Wave Propagation and Ground Motions**

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Strong ground motion in the Central and Eastern U.S. is generally carried by the regional phase, Lg, except at the closest distances to the source. Lg is usually defined by the observation of a high-amplitude wavetrain that arrives at a station with a group velocity of approximately 3.5 km/s. Phenomenological wave propagation models treat the Lg phase as a distinct, propagating crustal shear wave with a distance-dependent geometrical spreading parameter and an anelastic attenuation operator. Empirical fits of data using this model of Lg wave propagation are important to earthquake hazards mapping relating the gross behavior of ground motion with distance and magnitude of an event. However, the phenomenological model is not based on the actual physics of wave propagation within the continental crust and has limited use in determining structural and source influences on Lg wave amplitude. One indication of this is the large variation of amplitude residuals that occur in ground motion prediction equations. Studies of Lg using regional seismic arrays and dense networks of broad band stations show that Lg is not a single, propagating wave but is really a different wave at most distances. Lg is composed

of turning and/or critically reflected shear waves from the Moho that can experience many multiple reflections from the surface, depending on source-station distance. Horizontal phase velocities are high, ~4.3 km/s, indicative of propagation into the lower crust and the apparent existence of a single propagating Lg phase with a 3.5 km/s group velocity an illusion of heterogeneous seismic record sections. Broadband modeling of the Lg phase shows that very simple crustal models can predict the amplitude and arrival time of these turning and reflected arrivals quite accurately. Broadband modeling also shows that refraction-style crustal models consisting of a few layers often produces large, extraneous arrivals that are not supported by the data; smooth velocity models are necessary to reduce these modeling artifacts. Progress in predicting Lg wave amplitudes and times can be made through careful tomographic studies of earthquake broadband data and calculation of full wave seismograms through 1D, 2D and 3D physics-based wave simulation methods. These models will also form essential reference models for wave propagation simulations at higher frequencies where Lg and other regional shear waves are seen to exhibit wave scattering and significant coda production. Improvements in Lg wave observations can also be made through construction of regional seismic arrays within the CEUS.

### **Monitoring Hydraulic Fracturing Operations: From Micro to Macro Seismicity**

Shawn Maxwell, Schlumberger

The rapid expansion of unconventional oil and gas reservoir development, in particular shale oil and gas has been driven by the production advantages of large scale hydraulic fracturing of horizontal wells. Driven by this technological advancement, passive microseismic monitoring has grown into a common technology to map the resulting hydraulic fracture geometry. The detected microseismicity is often below moment magnitude zero, although the largest magnitude varies significantly between and within different reservoirs. Increased magnitudes are occasionally found in cases when the hydraulic fracture interacts with pre-existing faults. In extreme scenarios, these magnitudes can elevate from the micro to macro level and in rare cases result in the potential of induced seismicity that may be felt on surface. Microseismic observations thus provide important context to the issue of induced seismicity from hydraulic fracturing and other oilfield operations. The presentation will highlight microseismic observations from various injection rates and volumes in different formations, and examples of fault activation. Recent examples from the Western Canadian Sedimentary Basin of potential incidents of induced seismicity will be presented along with industry protocols created to assess and mitigate associated seismic hazard.



**“The Concussion has reached as far as we had had it in our power to receive information from” The Impact of Incomplete Historic Sources in New Madrid Earthquake Seismological Research.**

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Since the era of the first Jesuit seismologist, historic sources have been used to analyze seismic activity. Prior to the invention of accurate seismic instrumentation, the only data seismologists had for analysis were recorded reports of seismic activity coupled with their own observations of seismic phenomena. With the advent of modern instrumentation, the use of written historic accounts fell out of favor other than their use to catalog earthquakes and seismic activity. Several seminal studies identifying historic sources related to the 1811-1812 New Madrid earthquakes have been conducted, using historic sources to identify seismic phenomena related to them.

The map on this poster illustrates the effect that adding and correcting felt reports for the December 16, 1811 earthquake has on the Mercalli scale for locations affected by that seismic event. This poster shows part of the effort using historic sources to help us understand the New Madrid earthquakes. It introduces new data to better determine MMI values for the quakes and it corrects errors in historic data used in the previous studies.

**The 2014 USGS National Seismic Hazard Maps**

Charles S. Mueller & Members of the National Seismic Hazard Mapping Project, U.S.  
Geological Survey

The U. S. Geological Survey makes seismic hazard models and maps for building codes, emergency planning, risk management, and many other applications. The maps depict probabilistic ground motions for specified structural periods and risk levels. Seismic sources include: 1) specific faults with recurrence models developed from paleoseismic, geologic, and geodetic data, and 2) seismicity-based, areal “background” sources developed from earthquake catalogs. Ground motion estimates are based on empirical shaking data and modeling/simulation studies.

The maps are updated regularly to incorporate new data and research. We are revising the 48-State maps in 2014. In the central and eastern United States (CEUS) only a few faults are characterized well enough in slip rate or recurrence to be included directly. For 2014, in addition to updating New Madrid, Charleston, Meers, and Cheraw, new fault models for Wabash Valley, Commerce Geophysical Lineament, Reelfoot Rift Eastern Margin, Marianna, and Charlevoix are added based on recent research. Background seismicity sources, not faults, actually control the mid-to-high-frequency hazard in most of the CEUS. For 2014, a new moment-magnitude seismicity catalog is developed using current information on historical earthquakes. Treatment of non-tectonic earthquakes is a difficult challenge. Completeness and recurrence models for the background sources are updated based on analysis of the new catalog, and maximum-magnitude models are revised based on analysis of seismicity in stable tectonic regions worldwide. We implement a new nearest-neighbor algorithm to spatially smooth the background sources. Some elements of the source models have been adapted from the recently completed CEUS-SSC project. Results from the Next Generation Attenuation – East project are not ready for 2014, but

we are reviewing the established ground motion relations and incorporating new ones developed since the last update.

We welcome new research on these topics. Published results that find support within the scientific community are often incorporated directly into the maps. Uncertainties are large, and informed judgment and consensus are needed to develop and weight alternative models. Through a formal workshop-review-feedback process we bring the best available science to each step of the methodology.

## **The Effects of Induced Seismicity on Seismic Hazard**

Charles S. Mueller & Members of the National Seismic Hazard Mapping Project, U.S. Geological Survey

Pre-2014 versions of the National Seismic Hazard Maps gave special treatment to earthquakes suspected of being induced by underground fluid injection or extraction. They were deleted from seismicity catalogs because: 1) the causative process had ceased (Rocky Mountain Arsenal, CO), or 2) the causative process may have been ongoing but the earthquakes were considered too small to be hazardous (Rangely, CO; Paradox Valley, CO; Cogdell, TX; Dagger Draw, NM). In the past few years there has been a remarkable increase in CEUS seismicity, often in previously quiescent areas, and it has been suggested that many of these new earthquakes are induced. Our source models are based on natural earthquakes, but induced earthquakes are different: their maximum magnitude and recurrence may vary, and they may stop or start for commercial or policy reasons. Combined with their increasing numbers and sizes (magnitude 5.3 in Colorado in 2011, magnitude 5.7 in Oklahoma in 2011), this behavior presents new challenges. Given the large scientific unknowns, the human-control aspect, and the fact that the vast majority of injection/extraction procedures are aseismic, how do we estimate the hazard in a consistent way?

I compare results from two alternative quasi-end-member hazard models. Suspected induced seismicity is first identified in 14 zones and corresponding time windows (the above-listed areas plus central Oklahoma, Raton Basin, CO/NM; Guy-Greenbriar, AR; DFW Airport, TX; Youngstown, OH; and others). Model 1 abandons any pretense of estimating the hazard from these earthquakes and simply deletes them from the catalog. Model 2, in contrast, assumes that the most intense local swarm behavior is “the new normal”; seismicity counts are high and some are normalized over only a few years instead of decades, so model rates can be very high. Model 2 uses maximum magnitude 6 or 7. Ratios of probabilistic ground motions, Model 2 / Model 1, show local increases as great as factors of ten or more. Model 1 is consistent with the pre-2014 approach, and it is used for the proposed 2014 building code maps. To restore some of the missing hazard we are currently working with others (Rubinstein and others, this session) to develop alternative models and policy recommendations.

## **Initial ENA Empirical GMPEs Using the NGA-East Database**

Al Noman, M.N., and Cramer, Chris H., Center for Earthquake Research and Information, The University of Memphis, Memphis, TN, 38152

We develop an initial set of empirical ground motion prediction equations (GMPEs) for eastern North America (ENA) using the new Next Generation Attenuation (NGA) East ground motion database. This study provides predictive relationships for a particular measure of horizontal ground motion as a function of earthquake magnitude and fault type, distance from source to site, and local soil condition. We use the two-stage regression approach of Joyner and Boore (1993) and thus develop both within and between event sigma estimates. We also estimate single station sigma from stations with 30 or more recordings and obtain estimates for ENA of 0.3 as compared with total sigma estimates of 0.4–0.5 (natural logarithm). The resulting equations are for peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute-acceleration spectra (PSA) at periods between 0.02 sec and 2 sec. In our analysis we avoided records from the higher attenuating Gulf Coast region and used a total of 6544 records of PGA with a distance range from less than 10 km up to 3500 km. The available data for regression become less for longer periods. The developed empirical GMPEs, though not well constrained from large magnitude observations, fit the ground motions from small to moderate magnitude ( $M < 6$ ) earthquakes in ENA quite well based on residual analysis. The initial ENA empirical GMPEs will be improved in the near future by adding ground motion estimates from intensity observations for historical M6-7 earthquakes.

## **Topographic lineaments, liquefaction features, and possible fault rupture along the Cottonwood Grove fault in Blytheville, Arkansas**

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The Blytheville area of Arkansas is thought to be the epicentral region for the historical earthquake of December 16, 1811. The location of microseismicity appears to align on what some have called the Cottonwood Grove fault (or the Blytheville fault). However, the surface trace of this fault has not been located and may be partially destroyed or buried by fluvial processes. Newly acquired airborne Lidar data (U.S.G.S.) shows a NE-trending topographic lineament in the vicinity of microseismicity near Yarbrow, north of Blytheville. The linear ridge is approximately 1–1.5 m higher than the topography to the east and west and apparently has an *en echelon* trend with right-stepping segments. The anomalous topography appears to cross cut scroll bars, meander loops, and other geomorphic features along this portion of the Mississippi River flood plain. Our preliminary interpretations are that the topographic lineament represents the surface expression of an underlying structure, possibly a fault scarp, and that the geomorphic features cross cut by the neotectonic structure may provide piercing points for measuring fault

displacements. We plan to run ground penetrating radar and electrical resistivity tomographic lines across the lineaments to image the subsurface structure. Depending on our finding, we hope to excavate the structure and unravel its displacement history and begin to address the question of concentrated or distributed strain in the New Madrid seismic zone.

Four generations of earthquake-induced liquefaction features have been documented in the Yarbrow area and have been attributed to New Madrid earthquake sequences in A.D. 1811-1812, 1450, 900 and B.C. 2350. In the area, linear sand blows parallel the drainage of the Pemiscot Bayou and also cross cut the meander scroll bar morphology. In the fall of 2013, we mapped a recently exposed wall within the Yarbrow borrow pit adjacent to the dredged Pemiscot Bayou. Although the upper section has been disturbed in part, the underlying stratigraphic sequence shows at least two and possibly three generations of paleoliquefaction features constrained by layers of soil formation. In the upper part of the section, slightly iron-stained sand dikes cross cut a brown clay loam and may be overlain by remains of a “decapitated” sand blow. Radiocarbon dating of a piece of charcoal from the clay loam provides a close maximum constraining age of AD 1320-1350, 1390-1430 for these liquefaction features, suggesting that they formed during the A.D. 1450 event. In the middle of the section, a well-developed paleosol dips south and is offset and cross cut by sand dikes and overlain by a related sand blow showing multiple phases of venting. The radiocarbon date from the overlying clay loam suggests these liquefaction features likely formed during the A.D. 900 event, but additional dating of the underlying paleosol will help to establish their time of formation. In the lower part of the section, there is a sand layer that may represent an earlier liquefaction event. If so, it would help to further develop the New Madrid earthquake chronology and to reduce uncertainties of recurrence times of New Madrid earthquakes. Additional investigation is needed at the site to determine if the lower sand layer is connected to feeder dikes or if it is a fluvial deposit.

The relationship between topography, liquefaction features, and potential fault surface rupture in the New Madrid Seismic zone is an intriguing challenge. The pressurized slurry of water and sediment resulting from earthquake-induced liquefaction is likely to take advantage of any and all open fractures and faults, and in so doing, masks their surface expression. The new Lidar imagery, combined with knowledge of the subsurface from geophysical data and geological mapping has the potential to shed new light on the enigma of surface faulting in this portion of the New Madrid Seismic zone.

### **Comparing the CENA GMPEs using NGA-East ground motion database**

Luke P. Ogwen<sup>1, 2</sup> and Chris H. Cramer<sup>1, 2</sup>

1: The University of Memphis and

2: Center for Earthquake Research and Information (CERI)

The Next Generation Attenuation (NGA) East project has an updated database for Central and Eastern North America (CENA) ground motions. The objective of this study is to analyze the performance of ground motion prediction equations (GMPEs) used in the United States

Geological Survey (USGS) National Seismic Hazard Mapping Project (NSHMP) and some other potential GMPEs used in the CENA. Analyses include bias analysis and checks for model inadequacies using statistical tests such as cumulative probability plots, histograms and boxplots. Ranking of the GMPEs is accomplished using minimum residual, log likelihood (LLH), and Euclidean Distance Based Ranking (EDR) techniques.

From the classical residual analysis, Atkinson and Boore (2011) (model A08p), Atkinson and Boore (2011) (model AB06p) and Atkinson and Boore (2006) (model AB06+) with 200 bar stress drop performed better than other GMPEs. These results were also analyzed using box plots to summarize the location, dispersion, and symmetry or skewness of the residual values. In general the NGA East database is positively skewed i.e., the right tail is more pronounced than the left tail. This implies that most of the observed ground motion values are concentrated to the left of the mean, with extreme values to the right. GMPE logarithmic residuals are leptokurtic and non-normally distributed, although not strongly so. EDR results show models Atkinson (2008) (model A08), AB06p and AB06+ as the best performing models for combined site classes. Models AB06p, EPRI (2004) cluster2 model (EPRI2), AB06+ and Silva *et al.*, (2002) double corner model (SD02) matched the ground motion to the data well in rock sites. Generally, newer GMPEs tend to predict lower ground motion levels than older GMPEs. This is attributed to differences in the geometrical spreading used with the newer GMPEs using  $R^{1.3}$  versus  $R^{1.0}$  in the older GMPEs.

### **Debunking the Long-lived Aftershock Hypothesis, New Madrid seismic zone**

Morgan Page and Susan Hough, U.S. Geological Survey

It has been suggested that continuing seismicity in the New Madrid, central U.S. region is primarily composed of the continuing long-lived aftershock sequence of the 1811-1812 sequence, and thus cannot be taken as an indication of present-day strain accrual in the region. We examine historical and instrumental seismicity in the New Madrid region to determine if such a model is feasible given 1) the observed protracted nature of past New Madrid sequences, with multiple mainshocks with apparently similar magnitudes; 2) historical rates of  $M \geq 6$  earthquakes after the initial activity in 1811-1812; and 3) the modern seismicity rate in the region. We use ETAS modeling to search for sub-critical sets of direct Omori parameters that are consistent with all of these datasets, given a realistic consideration of their uncertainties. Our results imply that ongoing background seismicity in the New Madrid region is driven by ongoing strain accrual processes and that, despite low deformation rates, seismic activity in the zone is not decaying with time.



## **Central and Eastern U.S. Earthquakes Overview**

Christine Powell, CERl, University of Memphis

The existence of intraplate seismic zones in the central and eastern U.S. (CEUS) remains enigmatic; according to plate tectonic theory, distinct zones of seismic activity should occur only along plate boundaries. A number of consensus opinions regarding the occurrence of CEUS earthquakes were reached at the 2009 USGS workshop and can serve as a synopsis of our current understanding. These include 1) although the role of plate tectonics in driving intraplate earthquake activity is undeniable, thinking outside of the plate-tectonics box may be necessary to understand why intraplate earthquakes occur where they do. 2) CEUS seismicity appears to concentrate in distinct, identifiable zones. 3) Inherited structure in the crust and in the lithosphere from past tectonic events is important and can help us understand why earthquakes concentrate in certain places. 4) Inherited structure is not a sufficient condition for intraplate seismic activity; there must be other factors that play important roles in earthquake occurrence such as local perturbations in stress, strain and material properties, variations in temperature, and the presence of fluids. 5) Favorable orientation in the present-day stress field seems to be important. 6) The recurrence rate of large intraplate earthquakes may be telling us something fundamental about the physics of intraplate earthquakes that we do not understand. 7) Earthquake activity in the CEUS may migrate from place to place or may migrate within a seismic zone.

Assessing the hazard associated with intraplate seismic zones is difficult problem because we do not understand the causal mechanisms for the earthquake activity. Insight will be provided by the passage of USArray and by targeted FlexArray and magnetotelluric experiments aimed at better delineating inherited structure in the crust and lithosphere and flow patterns in the mantle. We will also benefit by physical and numerical modeling to determine the influence of known structure, intrusions, rates of deformation, and erosion on earthquake occurrence, clustering, and recurrence rates. Better instrumentation is needed to further our understanding of wave propagation and earthquake source physics in the CEUS. This might include installing borehole networks to record local seismicity away from surface sediments to observe source processes.

## **A Seismotectonic Model for the Eastern Tennessee Seismic Zone**

Christine Powell, CERl, University of Memphis

A seismotectonic model for the eastern Tennessee seismic zone (ETSZ) is proposed based upon a new local earthquake tomography study. The ETSZ is a major intraplate seismic zone with horizontal dimensions of 300 by 50 km and a vertical dimension of 25 km. The ETSZ is one of the most active seismic zones in the CEUS but has not produced a damaging earthquake in historical time. The zone is characterized by consistent focal mechanism solutions indicating strike-slip motion on steeply dipping planes. In the seismotectonic model, the ETSZ is attributed to reactivation of a major shear zone that accommodated juxtaposition of Amazonia and Laurentia during formation of the super continent Rodinia. P- and S-wave velocity models reveal the presence of a major, crustal-scale basement fault that provides a NW boundary to most ETSZ seismicity and corresponds to the prominent New York – Alabama (NY-AL) aeromagnetic lineament. Relocated earthquakes tend to align along steeply dipping planes that

trend NE and ESE, consistent with the focal mechanisms and suggesting the presence of a conjugate fault system. Reactivation of a major shear zone is compatible with growing evidence from paleomagnetic reconstructions that suggests the presence of a translational plate boundary between Amazonia and Laurentia during formation of Rodinia and with evidence from isotope geochemistry that the southern Appalachian basement is exotic to Laurentia.

### **Origin of the Blytheville Arch, and Long-term Displacement on the New Madrid Seismic Zone, Central U.S.**

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The southern arm of the New Madrid seismic zone of the central United States coincides with the buried, ~110 km by ~20 km Blytheville Arch antiform within the Cambrian-Ordovician Reelfoot rift graben. The Blytheville Arch has been interpreted at various times as a compressive structure, an igneous intrusion, or a sediment diapir. Reprocessed industry seismic-reflection profiles presented here show a strong similarity between the Blytheville Arch and pop-up structures, or flower structures, within strike-slip fault systems. The Blytheville Arch formed in the Paleozoic, but post-Mid-Cretaceous to Quaternary strata show displacement or folding indicative of faulting. Faults within the graben structure but outside of the Blytheville Arch also appear to displace Upper Cretaceous and perhaps younger strata, indicating that past faulting was not restricted to the Blytheville Arch and New Madrid seismic zone. As much as 10-12.5 km of strike slip can be estimated from apparent shearing of the Reelfoot arm of the New Madrid seismic zone. There also appears to be ~5-5.5 km of shearing of the Reelfoot topographic scarp at the north end of the southern arm of the New Madrid seismic zone and of the southern portion of Crowley's Ridge, which is a north-trending topographic ridge just south of the seismic zone. These observations suggest that there has been substantial strike-slip displacement along the Blytheville Arch and southern arm of the New Madrid seismic zone, that strike-slip extended north and south of the modern seismic zone, and that post-Mid-Cretaceous (post-Eocene?) faulting was not restricted to the Blytheville Arch or to currently active faults within the New Madrid seismic zone.

### 3D Velocity Models and Wave Simulations

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A description of the current Central United States Velocity Model (Version 1) and larger earthquake simulations of the three segments of the New Madrid Seismic Zone are presented. Plausible three-dimensional earthquake ground motion simulation scenarios based on the 1811-1812 New Madrid Seismic Zone (NMSZ) earthquakes demonstrate the importance of three-dimensional geologic structures, such as the Reelfoot Rift and Mississippi embayment. These structures strongly affect intensity, rupture directivity, amplify ground motions, and extend shaking duration. The numerical realizations represent the collaborative effort of three simulation groups with different numerical modeling approaches and computational capabilities. The set of 20 hypothetical earthquakes discussed include different magnitudes ( $M_w$  7.0, 7.6 and 7.7) and epicenters for two faults associated with the current seismicity trends in the NMSZ. The velocity model used is a compilation of decades of crustal research consisting of seismic, aeromagnetic, and gravity profiles; geologic mapping; geophysical and geological borehole logs; and inversions of the regional seismic properties, synthesized in a stand-alone spatial database that can be queried to generate the required input for numerical seismic-wave propagation simulations. The large scale computations shown demonstrate their potential use in providing insight not only on the wave propagation but also into the potential earthquake impacts on population and structures. Several improvements are required in the velocity model as well as in the frequency content of the numerically computed ground motions, which are outlined and discussed.

## **CEUS Ground Motion Models Used in the 2014 NSHMs**

Sanaz Rezaeian, Mark D. Petersen, Morgan P. Moschetti, Peter Powers, Stephen C. Harmsen, and Arthur D. Frankel

The 2014 update of the U.S. National Seismic Hazard Maps (NSHMs) includes modifications to the seismic source models and the ground motion models (GMMs) applied to sites across the conterminous U.S. This presentation focuses on modifications to GMMs relative to the 2008 update of the NSHMs. In the Central and Eastern U.S. (CEUS), three of the eight ground motion models used are new or have been modified since the previous version of the NSHMs. But the main changes are due to the modified weights applied in the construction of the mean ground motion. Relative model weightings are assigned by grouping the GMMs by model type (e.g., waveform model, hybrid model, etc.) and geometric spreading terms. Compared to the 2008 NSHMs, larger weights are applied to GMMs employing geometric spreading models that decay faster. As a result, the new GMMs and updated weights tend to decrease the probabilistic ground motions in the 2014 NSHMs relative to the 2008 NSHMs by 10-20% across most of the CEUS.

## **Quantifying the Seismic Hazard From Natural and Induced Earthquakes**

*Justin L. Rubinstein, Andrea Llenos, William L. Ellsworth, Arthur McGarr, Andrew Michael, Charles Mueller, Mark Petersen, U.S. Geological Survey*

Induced earthquakes are believed to be at least partially responsible for the dramatic increase in seismicity in the Central and Eastern US over the past 12 years, yet they are presently excluded from USGS estimates of earthquake hazard. Here we propose an approach to include potentially induced earthquakes into the USGS National Seismic Hazard Map that deemphasizes the need to evaluate whether the seismicity is natural or man-made.

We first compile a list of areas of increased seismicity, including areas of known induced earthquakes. Using areas of increased seismicity (instead of just induced earthquakes) allows us to assess the hazard over a broader region, avoiding the often-difficult task of judging whether an earthquake sequence is induced.

We then estimate the earthquake hazard for each zone using a four-branch logic tree: (1) The increased seismicity rate represents short-term variation within a longer-term background seismicity rate. Thus, these earthquakes would be included in the background seismicity rate catalog. (2) The increased seismicity rate is a new and permanent addition to the background seismicity. Thus, the background seismicity rate is computed beginning at the time of the earthquake rate change (3) Induced earthquakes are responsible for the increased earthquake rate and they should be accounted for separately. This branch would compute different magnitude-frequency distributions for both kinds of events. The hazard from both would then be summed (4) The increased seismicity rate will decay back to the background seismicity rate. This could be applied to natural earthquake swarms or areas where industrial activity has stopped.

Based on the understanding of an individual earthquake sequence, one could weight these logic tree branches as appropriate. Although an imperfect solution, this approach is a first step in accounting for the contribution of both induced earthquakes and variations in natural earthquake rates to seismic hazard.

### **Airborne geophysical survey data used to infer geological features associated with the 2011 Mw5.8 earthquake near Mineral, Virginia**

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We present analyses of airborne gravity, magnetic, and radiometric survey data flown over the 2011 central Virginia Mw5.8 epicentral area. These data were combined with detailed geologic mapping, geophysical sample measurements, and aftershock monitoring data in order to image surface and buried geologic structures. Aftershocks were mainly clustered along a tabular SE-dipping zone between depths of 3-8 km, interpreted as the causative fault. Smaller clusters of shallow (<4 km depth) aftershocks were also observed up to 15 km from the epicenter. Mapped metasedimentary rocks, metavolcanic rocks, granitoid intrusions and granitic gneiss show correspondences to gravity and magnetic anomalies in numerous areas, reflecting variations in density and magnetite content. Other anomalies do not show direct correspondences to surface rocks and most likely represent deeper geologic contrasts.

Near the Mw5.8 epicenter, a bend in major NE-trending features is observed in both geophysical and geologic data. Complex geologic contacts are mapped on the surface and several magnetic anomalies that are oriented obliquely to each other intersect in this area. Magnetic data which have been filtered to emphasize deeper sources suggest a contact between different rock types along the main-shock plane. Gravity data show a prominent NE-trending gradient extending >20 km in either direction from the epicenter; models of this gradient suggest presence of a shallow (2-4 km depth) low-density body within the hanging wall of the main-shock fault plane. Several shallow aftershock clusters show similar correspondences at a smaller scale: each cluster is located near both a gravity gradient and intersections between pre-existing faults and oblique magnetic anomalies interpreted as Jurassic dikes. The shallow aftershocks also occur near LiDAR lineaments (one which is mapped as a fault) that are coincident with radiometric potassium highs, suggesting potassium concentration due to muscovite crystallization during previous fault slip. These combined associations suggest that variations in rock density, rheology, and/or permeability modified local stresses in a manner encouraging localized seismicity.



### **3D Earthquake Simulations as a Tool to Gain Insight From Velocity Models**

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This presentation will offer a summary of recent work done using three-dimensional (3D) earthquake ground motion simulations to evaluate the accuracy of seismic velocity models and material attenuation rules. Special attention will be given to the analysis of results from simulations done using various models available for southern California as examples of what can be done in other regions with newly developed velocity models. In this order, a perspective will be offered on how similar and complementary approaches can be extended to the central United States (CEUS) region, and in particular, to the New Madrid seismic zone. Most velocity models currently available for simulations offer 3D descriptions of the crustal structure based on a combination of datasets drawn from exploration surveys, indirect measurements, inversion studies, and empirical approximations. In some cases, these models also include engineering measurements and rules intended to complement information about the uppermost (geotechnical) layers. In general they only offer information about P and S seismic wave velocities plus density, while attenuation parameters (i.e., the quality factors  $Q_s$  and  $Q_p$ ) are resolved using empirical relationships—usually extrapolated from other regions. Simulations done for the case of the southern California velocity models CVM-S and CVM-H show that the validation of synthetics using goodness-of-fit criteria that combine measures used in seismology and engineering, and the overall comparison of results with respect to empirical attenuation rules (NGAs/GMPes) can be used effectively to assess the accuracy of the material models. Such comparisons help highlight the aspects that are most relevant to the quality of the fit for any given region and event, and reveal the areas where attention is needed to improve and refine the models. This and the initial results published with the release of the seismic velocity model of the central United States (CUSVM) indicate that efforts done for other U.S. seismic zones are worth replicating in the CEUS region and the New Madrid area.

### **TECTONIC FRAMEWORK OF THE CENTRAL AND EASTERN UNITED STATES**

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Successive crust-forming and crust-modifying events contributed to the fabrics of the upper crust, which is now at seismogenic depths across the central and eastern United States. Aggregation of cratons, subduction, and terrane accretion led ultimately to craton stabilization and the anorogenic Granite-Rhyolite province (~1.5–1.3 Ga), which includes layered components and lateral boundaries. Two successive Wilson cycles of closing and opening oceans constitute the tectonic history of the central and eastern United States after ~1.35 Ga.

The Grenville orogen records assembly of supercontinent Rodinia by ~1.0 Ga. The Grenville Front is a crustal-scale structure that cuts across boundaries of older provinces. Multiple thermal events, geochemical characteristics, and geophysical boundaries indicate

internal terrane boundaries within the Grenville. In the Grenville foreland, sedimentary rocks are either rift-fill or foreland-basin deposits, and the Midcontinent rift system reflects extensional strain during the time of the Grenville orogeny.

Ages of synrift igneous rocks indicate diachronous continental rifting and breakup of supercontinent Rodinia between ~760 and ~530 Ma. Thick synrift sediment fills lower-plate rotated graben blocks and spaces along transform faults. Late synrift, rift-parallel and transform-parallel intracratonic faults extend inboard from the continental margin. Following opening of the Iapetus Ocean, post-rift thermal subsidence led to a passive-margin carbonate shelf; greatest magnitudes of thermal subsidence are along transform faults of the rifted margin and transform-parallel intracratonic faults.

The Paleozoic Appalachian-Ouachita orogenic belt (~485–280 Ma) records closing of Iapetus and assembly of Pangaea, and includes accretion of terranes along the Laurentian margin, foreland thrusting, and tectonic loading and foreland flexural subsidence. Foreland subsidence is greatest along transform faults of the Iapetan rifted margin. Reactivation of old rift-parallel and transform-parallel intracratonic structures reflects transpressional terrane accretion.

Rift segments and transform faults of eastern North America record breakup of Pangaea and opening of the Atlantic Ocean and Gulf of Mexico. Transform locations are inherited from Iapetan transforms; however, the rifted margin cut across Pangaeian sutures. The Mississippi Embayment south-plunging syncline overprinted Iapetan synrift and Pangaeian reactivated intracratonic structures.

A model for continental rifting includes a mechanism for a distributed-shear fabric parallel with transform faults in the mantle lithosphere, and a modern analog has seismic anisotropy parallel with the distributed-shear fabric. A transform-parallel distributed-shear fabric provides a mechanism for tectonic inheritance along transform faults and the projections of transform faults inboard from the rifted margin.

## **The Potential of Caves as Recorders of Datable Paleoseismic Events in the Central and Eastern U.S.**

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Reconnaissance of ~30 selected caves in the Ozark mountains of Missouri to the northwest of the New Madrid Seismic Zone (NMSZ), in southern Indiana near the Wabash Valley Seismic Zone (WVSZ), and along the trend of the northern portion of the East Tennessee Seismic Zone (ETSZ) from Knoxville, TN extending northeast into the northern Shenandoah Valley, VA reveals breakage of cave formations (speleothems) followed by renewed growth of secondary calcite has occurred within all three respective regions.  $^{234}\text{U}/^{230}\text{Th}$  dating of the youngest calcite in broken stalactites in the Ozarks shows timing of speleothem breakage events corresponds to major  $^{14}\text{C}$ -dated liquefaction events in the Mississippi Valley, including events at 1811-1812, A.D. 1450, A.D. 900, A.D. 300, and 2250 BCE (Tuttle, various citations). Panno (2009) shows that the onset of new speleothem growth events also corresponds to the Tuttle paleo-liquefaction chronology in the NMSZ. Although dated occurrences are limited, the Ozark results indicate earthquake effects are manifest in caves both as initiation of new growth and as termination of growth (breakage) of speleothems. A growing literature shows caves worldwide have successfully recorded earthquake events; we are seeking to employ the tool to learn more

about the paleoseismic history of the more problematic CEUS seismic sources. It seems appropriate to extend the approach to the WVSZ and to the ETSZ, where there is a significantly less complete and/or more problematic liquefaction record.

Although we have yet to date speleothem events in Indiana, reconnaissance of several caves from the Bloomington, IN area south toward the Ohio River reveals repeated episodes of speleothem breakage, with field relations similar to those that have been dated in the Ozarks. However, a number of these speleothems are somewhat larger than one typically observes in the Ozarks, an observation consistent with longer inter-event times for major quakes for the WVSZ compared to the NMSZ.

Reconnaissance of caves from Knoxville through Cumberland Gap and thence through western Virginia and the Shenandoah Valley also reveal repeated episodes of speleothem breakage and speleothem growth initiation events. However, many of the involved speleothems are significantly larger than those observed in Indiana, indicating that if earthquakes in fact damaged these ETSZ caves and caves in western Virginia, the inter-event times are significantly greater than either the ~500 year intervals for the Ozarks or the ~6000 year intervals indicated by paleoliquefaction studies in the Wabash valley.

U-series dating on good samples can extend back to about 350 ka-500 ka. Thus the technique can work for seismic zones with inter-event times vastly exceeding the limit of radiocarbon dating at 50 ka, which is widely used to date paleoliquefaction events. Successful application of this approach absent a paleoliquefaction “answer book” requires many samples to be obtained and dated, and those dates must cluster in time and to some degree in geographically, if earthquakes are to be invoked as the most likely cause of the observations.

A poster illustrating these findings and observations is available for viewing.

## **Quaternary Deformation, Geomorphology, and Model Testing of the Reelfoot Rift Region**

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The Reelfoot rift is a N45°E trending Cambrian rift that has controlled Quaternary deformation and current seismicity in the northern Mississippi embayment. Transpressional right-lateral strike-slip has occurred along the Commerce, northwestern Reelfoot rift margin, Axial, southeastern Reelfoot rift margin, and the Big Creek/Ellendale faults. Analysis of 3,931 (300-foot-deep) well logs reveals Quaternary uplift has also occurred along left-stepping compressional stepover faults bounding Joiner Ridge, Lake County uplift, and possibly the Meeman-Shelby fault at rates of ~2 mm/yr. Additionally, normal faults displace Pliocene Upland Complex of western Kentucky, Tennessee, and Crowley's Ridge suggesting that Quaternary right-lateral simple shear has extended across the entire Reelfoot rift to its outboard Commerce geophysical lineament/fault and Big Creek/Ellendale fault.

Previous investigators have mapped Wisconsinan braid belt terraces in the Eastern and Western Lowlands of the northern Mississippi embayment. This current research investigated the three-dimensional aspect of the Quaternary alluvium. In the Western Lowlands near Beedeville, Arkansas, the bases of three terraces descend ~20 m across a northeast-striking fault that coincides with the western margin of the Reelfoot rift. In traversing from west to east across the Eastern Lowlands, the base of the Quaternary alluvium/top of Eocene rises and the age of alluvium decreases. The base of the ~12 ka Morehouse braid belt and Holocene Mississippi

River floodplain averages 23 m higher in elevation than the older Wisconsinan floodplain bases. This high sub-alluvial surface (platform) is bound by the tectonically uplifted Joiner Ridge, Blytheville arch, Charleston uplift, and Bluff Line fault. The spatial relationship and similar histories of the platform and bounding structures suggest that their formation is tectonically related, possibly due to floodplain erosion within the last 12 ka.

These field observations provide testable models. 1) Confirmation of the E-W normal faults with seismic reflection can test the tectonic model of Quaternary right-lateral simple shear extending across the Reelfoot rift to its outboard Commerce and Big Creek/Ellendale faults. 2) Borings through the Mississippi River braid belts and floodplain can obtain OSL/C<sup>14</sup> dates to confirm the  $\leq 12$  ka age of the displaced alluvium thus testing the  $\sim 2$  mm/yr displacement rate of the stepover faults. 3) An Al<sup>26</sup>-Be<sup>10</sup> age of the faulted Upland Complex can determine if the current strain rate differs from the average strain rate since deposition of the (4 Ma?) Upland Complex. 4) Mapped faults and their slip rates can be used to build and constrain a numerical model of Quaternary Reelfoot rift deformation.

### **Recently Discovered Northeast-Oriented Transpression Structure in the Northern New Madrid Seismic Zone: Evidence of Shear Zone Extension Across the Reelfoot Fault Stepover Arm?**

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High-resolution seismic-reflection profiles acquired 12-km northeast of the New Madrid seismic zone's Reelfoot thrust and along the central axis of the Reelfoot rift imaged a set of steeply dipping N 30° E striking faults that have uplifted and arched post-Paleozoic sediments in a manner consistent with a dextral strike-slip component of displacement. The sub-parallel fault strands have been traced locally 1.4 km between reflection profiles. In an initial attempt to evaluate the structure's potential regional scale, the strike was projected northeast 22 km to its intersection with the nearest existing seismic image. This lower-resolution industry reflection profile exhibited a 0.75-km-wide structure with similar style and architecture at the intersection. The high-resolution images indicate the deformation extends above the Paleozoic bedrock, affecting Cretaceous and Eocene sediment, as well as crossing the base of the Quaternary. The Paleozoic and Cretaceous horizons show as much as 75 and 50 meters of relief, respectively, with the middle Eocene and basal Quaternary disrupted 25 and 15 meters, respectively. Geologic and geophysical logs from an adjacent borehole constrain the depth, velocity, and stratigraphic interpretations for the high-resolution data set. The faults, orthogonal to the Reelfoot stepover, are also too far inboard to be part of the rift boundaries; these preliminary data suggest the structure is part of the Axial fault zone that crosses the left-stepover Reelfoot thrust. Additional geophysical and geologic data are required to evaluate the spatial and temporal limits of these structures, as well as the range of their implications.